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Presentation/Paper Title	Author(s)	Date
"Final Report, Electra-Optical Imager and Radiometer(EOIR): An NPOESS Internal Concept Study"	J. Alishouse C.R. Rao	SEPT 95
"EO Sensor Design Studies, ICS Final Presentation and Report"	G. Rossano	28 SEPT 95
"EO Sensor Design Studies, ICS Final Presentation"	C.R.Rao	28 SEPT 95
"Calibration of the NPOESS E-O Sensor, ICS Final Presentation"	J. Alishouse	28 SEPT 95
"E-O Sensor Hardware Design Characteristics, Final Report and Future Study Recommendations"	-----------	SEPT 95
"E-O Band Selection for NPOESS Based on Key Parameters"	D. Lynch	SEPT 95
"EO Imager Baseline Requirements Presentation"	-------------	JUNE 95
"ICS Interim Status Review Meeting, Electro-Optical Imager & Radiometer"	D. Lynch	29 JUNE 95
"ICS Interim Status Review, EO Imager & Radiometer:	C.R. Rao	29 JUNE 95
"ICS Interim Status Review, Calibration Issues for the NPOESS E-O Sensor"	J. Alishouse	27 JUNE 95
"EO Imager ICS- June Progress Report"	Lt. K. Westley	20 JUNE 95
"EO Imager ICS- May Progress Report"	Lt. K. Westley	I6 MAY 95
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"EO Sensor Baseline Design, EO Sensor Progress Report Briefing", (draft copy)	G. Rossano	21 APRIL 95

Electro/Optical Band Selection for NPOESS Based on Key Parameters

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Electro/Optical Band Selection for NPOESS Based on Key Parameters

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EXECUTIVE SUMMARY

Based on the Key Parameter EDRs, we have identified eight bands for use on NPOESS. They are two narrow visible, one broad visible and four narrow IR bands at roughly 1.7, 3.6, 8.4, 10.6 and 11.5μm. We have also recommended having a set of minimum quality thresholds on the imagery irrespective of any parameter, whether key or non-key. A number of important issues remain to be clarified including the meaning of "aerosol" and "cloud", the necessity for both day and night extraction of all EDRs, the need for absolute radiometric calibration and the role of algorithms. Owing to the importance of and on-going development of algorithms necessary to interpret the imagery as well as the large number of TBD thresholds in the present system specification document, further system specification cannot be done until these issues are resolved.

1. INTRODUCTION

The following document summarizes the sensor performance characteristics required to meet the NPOESS EDR Key Parameter requirements. Non-key parameters and microwave systems are not considered here. The main goal is to identify and justify the number of bands in the visible and infrared (IR) that are directly derivable from and traceable to key parameter EDRs.

2. TOP LEVEL REQUIREMENTS

The NPOESS Interface Data Processor (IDP) will take Raw Data Records (RDR) and convert them to Environmental Data Records (EDR) using existing and future algorithms. For example, to meet one aspect of the Imagery EDR, the NPOESS will take voltages in an infrared pixel, calibration data, satellite positional information, etc. and produce an absolutely calibrated image of a known part of the earth. The EDRs and their specifications are set forth in the Draft Integrated Operational Requirements Document (Wilczynski, 1994).

The EDR requirements are presently incomplete and many EDR parameter specifications are TBD. This is because of the complexity of taking thousands of diverse requirements from different users with different measurement goals and condensing them into a simple, coherent, achievable requirements set. Clarifying the EDRs and replacing the TBDs with actual values is one goal of the Internal Concept Study (ICS). We begin with the clarification of four items: Day/Night Requirements, Cloud/Aerosol Screening, Calibration, and Algorithms. <u>Until these issues are resolved, it will not be possible to complete a flow down of the EDR requirements mto a system specification.</u>

A. Day/Night Requirements

The IORD is vague as to whether some or all threshold EDRs are to be met both day and night. Individual EDR's occasionally refer to day/night operation but no uniformity is presently in place in this area. Day time imagery is obtained primarily by detecting scattered sunlight (λ < 4 urn). Night time imagery is obtained by detecting thermal emission from the ground and atmosphere (λ > 3.5 urn). Previous satellites lie GOESS have used the 3.8 - 4.0 μm band which is a mixture of both emitted and scattered light, the latter being used during the day and the former at might. Daytime imagery may be better in terms of Horizontal Spatial Resolution (HSR) and calibration. It also has the advantage of being more comprehensible to a human analyst whose intuition regarding relative brightness, shadows, etc. fails or is less certain with thermal imagery. Thermal imagery, on the other hand, has the very great advantage of operating both day and night. Therefore, *any EDR threshold that must be satisfied at night must be derivable from thermal IR sensors alone. The system performance may be. enhanced during the day using visible sensors. Microwave sensing could in principal also be used but the horizontal spatial resolution*

(HSR) is far too poor to be considered. This guiding concept is intended to eliminate earlier notions that the system performance that meets the EDR thresholds during the day "may be degraded at night." Such degradation implies that the threshold would not be met at night, and therefore would not satisfy the EDR threshold.

While it is probably very difficult to meet all EDR thresholds day and night, it may be possible to do so for the two most stressing key parameters, specifically the *Imagery and *Sea Surface Temperature. Based on discussions with the Joint Agency Requirements Group (JARG) and their representatives, we will proceed on the assumption that key parameters (only) must be met both day and night. **We recommend that the JARG address the day/night requirements issue with the user community and formulate an explicit response to resolve the matter. implementation would be to specify which EDR's are to be met day and night and which are only required day or night.**

Notes: The 3.8 - 4.0 μm channel would satisfy both day and night requirements but would produce an inhomogeneous data set because it mixes thermal and scattered radiation and transitions from one to the other with every passage across the terminator. The requirement for both day and night retrieval of Sea Surface Temperature may be implicit in the refresh threshold requirement of six hours. Requirements Issues #13 (RI#13) for the now defunct "Cloud Imagery" EDR states that the requirements are to be met both day and night. An explicit statement to this effect should be included in each EDR to which it applies.

B. Cloud/Aerosol Screening

An aerosol is any collection of solid or liquid particles suspended in the atmosphere(Hutschke 1959). Clouds, fog, volcanic ash, polar stratospheric clouds, sea spray, wind-blown dust, smoke, haze and smog are all aerosols. Each aerosol particle absorbs, emits and scatters light with a different spectral signatures. If enough detector channels are used, the signatures can be used to, identify and if necessary remove the effects of the aerosols from the radiance measurement. If too few channels are used, then a model must be used that represents a "composite" aerosol. There is no such thing as a "typical spectral signature" that fits all aerosols, as the EDRs might suggest.

Scattering and absorption by atmospheric constituents (gases + aerosols) will attenuate surface light and introduce atmospheric radiance. Emission from the aerosols will add its own contribution to the signal. An IDP production of an EDR that refers to the surface (e.g. Sea Surface Temperature) must correct the radiance image for the effects of aerosols. To do this, the aerosol must be detected. For example, determining cloud cover involves detecting clouds, locating their boundaries and computing their areas. The opacity of a cloud decreases rapidly near its edge, and a limit exists beyond which the cloud is simply too thin to detect. Yet the undetected cloud still influences light propagating though it. If a particular region (pixel) is deemed cloud-free, no algorithm can be applied which will correct for the undetected cloud and therefore any derived product (e.g. sea surface temperature) will be in error, often by a considerable amount (see below). Furthermore, an algorithm optimized to detect thin cirrus clouds over the ocean may not detect a thin stratospheric cloud of volcanic ash. The algorithm will also give an incorrect answer as to the nature of a thin cirrus cloud in the presence of volcanic ash.

In a related matter, suppose that as an interpreter of satellite imagery, you are presented with a scene that is cloud-free, yet shows large amounts of aerosols. Such an image might, for example, be taken of Los Angeles on a smoggy day or when there is significant smoke from a brush fire. During the summer there is also considerable low fog in the morning and marine haze in the afternoon. It might be possible to perceive ground detail but at a reduced contrast. How is this scene to be characterized? Is it smog, smoke, fog, haze, or what? What is the opacity? How does it vary with wavelength? Since it is a cloud-free scene, is sea surface temperature supposed to be determined through the obscuring matter? These questions should be addressed in defining the relevant EDRs.

The NPOESS specification documents presently have no definition of an aerosol. It does, however, seem to make the distinction between "cloud", "aerosol" and "suspended sediment", apparently because of the belief that each is fundamentally different from the other. The thinking seems to be that clouds are made of water (and ice), aerosols are somehow different than clouds and are like smog or haze, and that suspended sediment is something altogether different, like airborne dirt or volcanic ash. Both scientifically and operationally, clouds, haze, smog, ash and airborne dirt are all aerosols. From an E/O standpoint, all aerosols have similar properties: they are suspensions of particles that absorb, scatter and radiate light. Distinguishing one aerosol from another depends on its spectral properties. Since there are an infinite variety of aerosols, there is an infinite number of spectral signatures. It makes more sense to identify the most common aerosols and write specs for each one of them. I would suggest the following.

AEROSOL	CONTENT
1. water cloud	liquid H20
2. ice cloud	solid H20
3. volcanic dust cloud	solid silicates
4. windblown dust/sand	solid silicates, carbonates
5. industrial smog	liquid solution of $H_2SO_4 + H_2O$ + other compounds
6. stratospheric aerosols	liquid, solid TBD
7. wood fire smoke	solid hydrocarbons
8. oil fire smoke	solid hydrocarbons

An undetected aerosol will not contribute to the radiance error budget but will influence the derived brightness temperature of the surface. The relation between uncertainties in physically measurable quantity (radiance) and their influence on derived property (brightness temperature) is illustrated in the following example. A 280 K black body's radiance at 10 μm varies by about 2% for each degree Kelvin of temperature change. If we imagine that the ocean is a black body at 280 K and we view it through an undetected aerosol that reduces the radiance by 5%, the resulting temperature error would be about 2.5 K, five times larger than the threshold EDR specification of 0.5 K. An aerosol that transmits 95% of the radiation incident upon is nearly undetectable by today's standards.

Detection of the aerosol is the first step and opacity is the pivotal quantity (See Appendix I for a discussion of opacity). Since the detectability of an aerosol depends on its opacity, we recommend that a minimum opacity criterion should be included in the definitions of both cloud and aerosol and that recognition of the aerosol nature of ordinary clouds be made. This specification should be derived from (rather than imposed upon) the radiometric accuracy criterion.

C. Calibration

The imagery EDR does not explicitly state the radiometric accuracy to which imagery is required, only that it be "absolutely calibrated". Today's state-of-the-art satellite sensor systems can, if specially designed for this purpose, generally achieve absolute calibrations to around 1-5% in the visible and 5- 10% in the thermal infrared. The precision, i.e., the ability to detect a change or difference, is better, on the order of 1/2 %.

The National Institute of Standards and Technology (NIST) position on calibration is that with a single detector, in a controlled environment, they can routinely do absolute radiometry to about 1%. This of course, is in the laboratory where detectors, filters, temperatures and emissivities can be closely monitored. Space calibration is a good deal more difficult. For example, the MODIS goal is to calibrate to < 1% (Godden, Knight and Guenther 1995). To do this, the moderate resolution Imaging Spectrometer (MODIS) must employ a continuously-rotating mirror which looks at an on-board black body, space and the earth every scan. The temperature of the black body must be known to < 0.1 K, the scan mirror temperature to < 1 K and scan mirror emissivity to <0.1%. Stringent requirements are also placed on filter out-of-band rejection, off-axis scattered light and scattered light as a function of scan mirror position. MODIS is depending on certain material properties (like emissivity) not changing after launch, an assumption that the long duration exposure facility (LDEF) people found to be unreliable.

One way to determine the required IR accuracy is from the Sea Surface Temperature accuracy of ±0.5 K. As noted above, the 10 μm brightness of the earth varies by about 2%/K in the absence of any atmosphere or aerosols. Therefore a 0.5 K uncertainty would translate to about 1% in the IR radiometry. This is presently difficult if not impossible to achieve on a satellite system. Even in the laboratory, making absolute radiometric measurements to 1% is difficult in the visible and very challenging in the infrared. Also note that the presence of the atmosphere and aerosols makes it impossible to retrieve temperature simply by inverting the Planck function. A model of the atmosphere appropriate to the observations is necessary, the most critical portions of which are the temperature and water vapor profiles.

We recommend that a radiometric accuracy be specified. Alternatively a signal-to- s e should be set. This is not the same as specifying sensor response, etc. It is an EDR threshold requirement and should be included in the EDR. Since system sensitivity drift occurs in virtually all sensors, there must be a way of tracking these drifts so that the calibration can be maintained. The system designers should also specify how the calibration will be verified during on-orbit operation.

D. Algorithms

The EDRs require two types of algorithms. (1) Calibration algorithms are used to convert raw data into calibrated data (e.g. detector output in volts will be converted into radiance in watt m^{-2} μm^{-1} sr^{-1}.) They are designed to produce the highest quality radiometric products. Calibration algorithms involve system issues such as detector sensitivity, background noise, detector nonlinearities, calibration sources, amplifier drift, scattered light, optical degradation, etc. In general, calibration algorithms are not concerned with scene content except for brightness. There is presently considerable experience in the scientific and engineering communities with calibration algorithms. (2) Interpretation algorithms take (usually) calibrated data and retrieve a more specialized kind of information (e.g. one interpretation algorithm will take infrared radiance imagery produced by calibration algorithm and, possibly with other data products, generate a cloud/no cloud map.) These algorithms are generated and verified using ground truths, data collects, model computations, etc. and there is often little or no quantitative criterion for success other than that a "trained analysts" has guided the algorithm development and thinks that it "does a good job" under most circumstances." Interpretation algorithms are generally "softer" and less specific than calibration algorithms. They often contain "free parameters" which can be varied according to the situation. They are ever-evolving and sometimes still in the "research" stage.

The reason for identifying the two types of algorithms is for clarity. The Imagery requirement should be concerned primarily with calibration algorithms but as presently written it implicitly includes interpretation algorithms. The requirement that cloud types be distinguished requires both calibration algorithms to provide radiance levels (a key tool in cloud discrimination) and interpretation algorithms to distinguish one cloud type from the next.

We recommend that the imagery EDR be written in such a way that it requires only calibration algorithms. This is because imagery should be independent of scene content. The Sea Surface Temperature specification, in contrast, cannot be written in this way because it is scene specific and cannot be produced by calibration imagery alone. A calibrated thermal radiance image of the ocean cannot be directly inverted to give sea surface temperature because the sea does not emit like a black body and there will always be intervening air and aerosols that will modify the radiance from the sea surface. To remove atmospheric effects, interpretation algorithms that involve temperature profile, humidity profile, aerosols, cloud detection, etc. must be brought to bear.

Retrieving properties such as sea surface temperature, cloud type, and degree of cloud cover requires algorithms. Some of these algorithms are well defined, other are not. Before a band(s) can be positively defined, a demonstrably successful algorithm must also be defined. Thus band specification and algorithm identification go hand in hand for certain EDRs.

3. KEY PARAMETERS

The list and character of the key parameters has changed dramatically during the last year. Therefore, instead of attempting a flow down based on the system specification document which is almost a year old, I will instead discuss the key parameters in light of the most recent thinking and suggested modifications. Most important among theses is the imagery specification which now explicitly will include clouds and sea ice. The E/O key parameters that largely define the system are Imagery (including clouds and ice) and Sea Surface Temperature and each is discussed below.

A. Imagery

Throughout the course of the Internal Concept Study, "imagery" has been the EDR most often discussed. And for good reason. The NPOESS imagery will be one of the most valuable products of the system. The imagery will be both direct and derived ("interpreted"). Direct imagery will consist of calibrated radiance images in a certain band such as the visible. There will be a radiance and an uncertainty associated with each pixel (or alternatively signal-to-noise ratio SNR) and each pixel will have a certain latitude and longitude associated with it. The image will have a certain horizontal spatial resolution (HSR) that will vary across the field. Derived imagery such as sea surface temperature will be produced by algorithms that use two or more images from different bands in an algorithm. At the present time the algorithms have not been fully defined or optimized and there will surely be new algorithms developed in the coming years.

Owing to the fundamental importance of imagery, both direct and derived, and to the continuing expansion of our ability to interpret imagery via improved algorithms, we recommend that a minimum image quality specification be placed on all direct imager. This minimum specification should reflect hard thresholds on horizontal spatial resolution, mapping accuracy, signal-to-noise ratio, band purity and dynamic range. Since many of the EDRs are new and incomplete, and since the algorithms for them have not been identified, it is difficult to specify the thresholds at this time. However, they should look something like this.

1. horizontal spatial resolution (HSR)	
global	2.4 km
local	0.65 km
2. mapping accuracy	0.5 km
3. minimum signal to noise ratio	100:1
4. dynamic range	100000:1

Notes: (1) Horizontal spatial resolution will be determined by several agents acting together: diffraction limit of the optics, detector size, nadir angle, sampling time, etc. As a rule, the worst spatial resolution will be at the largest nadir angle and will vary roughly as the secant of nadir angle. Since secant approaches infinity for nadir angle of 90" , it will be virtually impossible to maintain any reasonable HSR near the planetary limb. Therefore the maximum nadir angle must be defined before a HSR threshold can be established, Alternatively, we suggest establishing a horizontal angular resolution spec, a quantity that is nearly constant over the field of view.(3) this is driven by the absolute radiometric calibration requirement of approximately 1%.

It is likely that the EDRs will ultimately drive these imagery thresholds to more stringent levels. It is also possible that in some cases the EDRs may suggest relaxing them below the levels indicated. In addition to the minimum imagery specifications above, the imagery must be of sufficient quality to meet the EDRs once the TBDs have been replaced with firm numbers.

B. Sea Surface Temperature (SST)

Sea Surface temperature is an imagery product, though not necessarily explicitly included in Imagery. The following comments should be considered in evaluating the SST requirements

1. Absolute Sea Surface Temperature must be determined to ± 0.5 K. Temperature in this context is a derived parameter and depends on the use of an interpretation algorithm. As noted above, it is an extremely challenging goal.

2. "Infrared cloud/no cloud" determination must be made. This requires going back to the definition of cloud and aerosol.

3. A spec of ± 0.5 K absolute is extremely challenging. In general such measurements can only be done in specially equipped laboratories and even then, with difficulty.

4. BAND SPECIFICATION

The key parameter EDRs discussed above flow down to eight bands.

BAND 1 Daytime visible imagery is best performed in the red end of the visible spectrum. This allows imagery to be taken in the most sensitive part of a silicon detector's range which is still within the visible (as defined by the eye). Using it for visible imagery is like taking a B&W picture through a red filter. The lower cut-off wavelength (0.58 µm) can be made even lower with a potential gain in signal and little loss of performance due to additional molecular scattering in the atmosphere. The upper cut-off wavelength (0.68 µm) can not be increased because to do so would include the terrestrial B-band of molecular oxygen. Alternatively a visible band could be placed long ward of 0.7 µm where the atmospheric opacity is lower and the detector sensitivity is higher. Exact bands can be argued but the visible daytime band should be somewhere in the range 0.6 - 0.8 µm with a bandwidth of the order of 0.1 µm

BAND 2A second daytime visible band would be extremely useful in detecting and identifying aerosols, especially thin clouds, marine haze and smoke. The precise band specification will have to await clarification of the aerosol issues raised above. To minimize molecular scattering effects it would be desirable to have the band in the 0.5- 0.6 µm region. To maximize particle discrimination, a shorter wavelength (0.4-0.5 µm) would be better.

BAND 3 Historically low light level images have been useful and it is expected that they will continue to find utility on NPOESS. Therefore a low light band (0.4 - 1 .O µm) is probably appropriate for NPOESS.

BAND 4 Obtaining imagery at night will require a band that detects thermal radiation from the earth and atmosphere in the LWIR window between the water vapor absorption near 8 µm and the CO2 absorption near 13.5 µm. It should be just long ward of the ozone band at 9.6 µm and located in the wavelength region of the peak emission for optically thick clouds (9.7 - 12 µm.) Band 3 will be used in conjunction with band 4 (below) to determine brightness temperature and cloud type. Resolution will depend on many things in concert: telescope diffraction limit, detector size in image space, scan/sampling rate, satellite altitude or distance from target will also directly affect resolution. The system must be designed to achieve the desired resolution. There is no signal-to-noise spec or radiance accuracy spec in the EDR for visible cloud imagery. This must be resolved in order to define the system. Since Band 3 will be expected to operate at night, it must meet all the EDR's including the requirements for threshold horizontal spatial resolution and the absolute radiance calibration. Tentative band specification: 8.3 - 9.1 µm.

BAND 5 Algorithms exist that can produce brightness temperature from radiance measurements (as in band 4 above) in the LWIR. A more accurate temperature determination, especially in the presence thin or high clouds), can be obtained by adding a second LWIR band. In this way two brightness temperatures and one color temperature can be computed based upon the ratio of the two bands. This band (tentatively 10.5- 11.3) will also be necessary in cloud type discrimination. Water/Ice Cloud Discrimination can be done using Band 4 and Band 5 together.

BAND 6Detecting high thin cirrus is crucial to determining SST, ground temperatures and earth radiation budget. In conjunction with bands 5 and 6 this band will not only allow for the detection of thin cirrus it will also argument and enhance SST retrievals (d'Entrement et al. 1992; Sanders and Kreibel 1988). Tentative band selection is 11.6 - 12.5 µm.

BAND 7Snow/Low Cloud Discrimination has been done during the day using the 1.5- 1.8 µm band since 1994 when such a band was flown on NOAA K in 1994. No technique has been developed to do it at night. Therefore if there is a night time requirement on this measurements, new bands will have to found and exploited and new algorithms will have to be developed. At the present time there is no known ways to distinguish snow on the ground from a low thick ice clouds in the thermal IR (Crane and Anderson 1984).

BAND 8Fog and low cloud discrimination remains one of the most challenging issues in remote sensing to day. The most successful technique involves the use of the 3.6 µm.

It is important to realize that the bands selected above are not unique, only representative of bands that are known to perform well enough to be considered as candidates for the NPOESS system. By changing the bands or bands widths slightly it may be possible to optimize them within the context of a specific algorithm, Until the algorithms are defined, optimization may not be possible.

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Appendix I Aerosol and Cloud Opacity

Light passing through a cloud is attenuated by absorption and is scattered out of the beam. At the same time light may be introduced into the beam by scattering or thermal emission. Both processes must be considered when computing cloud radiances and the starting point of the calculation is the transfer equation.

$$dI/d\tau = S - I$$

where I is the radiance of the cloud, τ is the optical depth and S is the source function. Solving for I requires integrating this equation and satisfying whatever boundary conditions are applicable. A simple yet particularly useful solution to this equation is

$$I = 10\ e\text{-}r + S\ (1 - e\text{-}r) \qquad (1)$$

where 10 is the brightness of the beam before entering the cloud and I is the brightness after leaving the cloud. The first term represents loss and the second term gain. Note that when τ = 0 (no cloud) then I = 10 and when τ = _ then I = s.

Optical depth has two components, scattering and absorption, which together are termed extinction.

$$\tau_{EXT} = \tau_{SCA} + \tau_{ABS}$$

The optical depth of a cloud is given by

$$\tau_{EXT} = N\sigma_{EXT}\ L = N\ (\sigma_{ABS} + \sigma_{SCA})\ L$$

where N is the number density of particles (cm^{-3}), σ_{EXT} is the extinction cross section (cm^2) and L is the line-of-site distance through the cloud (cm). Note that τ is unitless. σ_{EXT} (= σ_{ABS} + σ_{SCA}) can be written

$$\sigma_{EXT} = Q_{EXT}\ A$$

where Q_{EXT} is the extinction efficiency and A is the cross sectional area of the particle. For spheres of radius r,

$$\sigma_{EXT} = Q_{EXT}\ ' r^2 = (Q_{ABS} + Q_{SCA})\ ' r^2$$

The most difficult aspect of computing τ is surely the computation of Q_{EXT}, QABS and QSCA. Analytic solutions exist only for spheres ("Mie theory") where only the complex index of refraction (n,k) and r are necessary for the computations. For nonspherical or irregularly shaped particles (like aerosols such as ice clouds, smoke, dust cloud, etc.), the computations are extremely difficult because numerical algorithms must be used and shape, orientation and size must be used in the calculation. For some large, irregular particles the efficiencies simply cannot be computed.

It is sometimes necessary to compute the scattering profile $\phi(\theta)$ of the particle (sometimes called phase function). $\phi(\theta)$ describes the relative amount of light scattered into the angle θ for a spherical particle. If the particle is nonspherical than the profile has two independent variable $\phi(\theta,\varphi)$ corresponding to the entire celestial sphere of 4 ' steradians.

With the scattering cross sections, phase functions, number density, particle size distribution and in the thermal IR, atmospheric temperature profiles in hand, the parameters are plugged into radiative transfer codes which compute the radiance. Radiative transfer codes vary between fairly simple formalisms like the one shown analytically in equation (1) above to massive computer codes that work at very high spectral resolution, include multiple scattering and a variety of boundary conditions such as hard earth spectral radiances for sea, desert, vegetation, etc. The codes most familiar to DoD/NOAA are LOWTRAN7, MODTRAN, FASCODE, etc., all supported by Phillips Laboratory (Anderson et al. 1994)